TITLE: Progress in Heterostructure Barrier Varactor Frequency Multipliers

Progress in Heterostructure Barrier Varactor Frequency Multipliers

Jan Stake, Mattias Ingvarson, Lars Dillner, and Erik Kollberg

***Abstract* – The Heterostructure Barrier Varactor diode and its performance as a varactor frequency multiplier is reviewed.**

I. INTRODUCTION

The Heterostructure Barrier Varactor (HBV) diode which was introduced about ten years ago, Kollberg and Rydberg [1, 2], is a strong candidate for high power frequency multipliers at millimetre and submillimetre wave frequencies. Since the HBV has a symmetric capacitance-voltage (C-V) characteristic, it operates unbiased and will only produce odd harmonics when pumped with power at the fundamental frequency, f_p. The absence of even harmonics simplifies the realisation of higher order multiplier circuits. For the tripler case, it is possible to build a multiplier circuit considering the pump frequency and the output frequency only. As a result of the simplified circuit, design of frequency triplers and quintuplers operating over a wider frequency range is possible. An important advantage of the HBV diode compared to the Schottky varactor diode is that several barriers can be epitaxially stacked, which increases the power handling capability considerably, Krishnamurthi *et al.* [3] and Rahal *et al.* [4]. Hence, an HBV diode can be tailored for a certain application in terms of both frequency and power handling capability.

Recently, HBVs have been fabricated on a copper substrate to improve their heat sinking capability [5]. These devices can be designed to handle at least one Watt of input power and yet maintain the device temperature below 100°C. For a single twelve-barrier HBV, a realistic conversion efficiency of 10% is expected, thereby providing output power in the region of 100 mW at 250 GHz. This could then be used to drive an HBV quintupler to provide milliwatt levels of power at THz-frequencies.

II. MATERIAL SYSTEMS

The HBV consists of a high bandgap semiconductor sandwiched between low bandgap semiconductors. The high bandgap material (barrier) prevents electron transport through the structure. When the structure is biased, electrons are accumulated on one side of the barriers and depleted on the other side of the barriers. The resulting C-V is shown in Fig. 1. It is necessary that the barrier material and the depletion layer material have almost the same lattice constants to avoid lattice dislocations and inferior performance. However, it is possible to grow dislocation free layers with a small lattice mismatch if the layers are thinner than a critical thickness. The first HBV diode was realised using GaAs/$Al_{0.7}$GaAs grown on GaAs [2]. The GaAs/AlGaAs material system is well characterised and relatively simple to process. A drawback with this device is the comparatively large conduction current due to a low conduction band offset and, hence, a corresponding low barrier height. The conduction current deteriorates the efficiency. It has also been shown that the temperature increases when the diode is pumped, which further increases the conduction current and leads to an even lower efficiency, Stake *et al.* [6].

The material system $In_{0.53}GaAs/In_{0.52}AlAs$ grown on InP offers a larger conduction band offset, which results in a lower conduction current and an improved varactor performance. It is also possible to increase the effective barrier height even further if a thin layer of AlAs is inserted in the middle of the barrier. It is very difficult to grow thick epilayers of high quality on InP by MBE. Thick epilayers are needed for planar HBVs, since they use thick buried contact layers, and for HBVs with a large number of barriers. However, it has recently been shown that very good HBV material can be grown by MOVPE, Strupinski *et al.* [7]. A material grown by MOVPE is presented in Table I. The structure, originally designed for planar devices, is similar to HBV materials grown by MBE, but with larger undoped spacer layers to prevent diffusion of silicon into the barrier layers.

Table I ITME 1817 layer structure

Layer	Material	Thickness [Å]	$\lvert N_D - N_A \rvert$ [cm^{-3}]
12	InAs	100	$>5.10^{18}$
11	In_xGaAs x=0,53→1	400 (layers 11–10)	$>5.10^{18}$
10	$In_{0.53}GaAs$		$>5.10^{18}$
9	$In_{0.53}GaAs$	4000	3.10^{16}
8 x 6	$In_{0.53}GaAs$	200	undoped
7 x 6	$In_{0.52}AlAs$	50	undoped
6 x 6	AlAs	30	undoped
5 x 6	$In_{0.52}AlAs$	50	undoped
4 x 6	$In_{0.53}GaAs$	200	undoped
3	$In_{0.53}GaAs$	4000	3.10^{16}
2	$In_{0.53}GaAs$	3000	$>5.10^{18}$
1	InP		$>5.10^{18}$
Subst.	InP		N^{++}

A lower doping concentration in the depletion layers results in a higher breakdown voltage and a low minimum capacitance. Typically a current density $\leq$ 0.1 $\mu A/\mu m^2$ is required for good efficiency, yielding a

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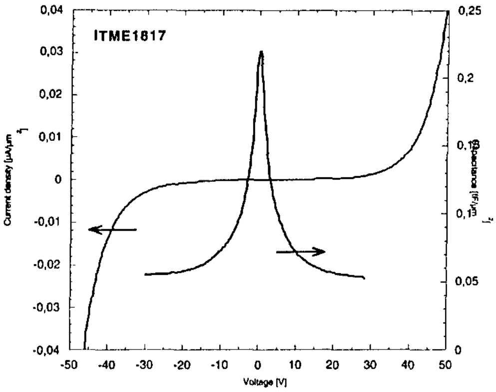

Fig. 1. Current density versus voltage and C-V characteristics for a six-barrier HBV (ITME 1817).

maximum voltage of 8 V per barrier for $N_d = 3\cdot10^{16}$ cm^{-3} in the depletion layers. A drawback with a low doping concentration is that it results in a high resistivity which increases the losses and decreases the dynamic cut-off frequency. MOVPE material is now equal in performance to MBE material, Strupinski *et al.* [7], Lheurette *et al.* [8].

III. HBV DESIGN AND ANALYSIS

For a varactor multiplier, the conversion efficiency is related to the ratio of the pump frequency and the dynamic cut-off frequency $f_c = (S_{max} - S_{min})/2\pi R_s$, where R_s is the series resistance, S_{max} and S_{min} are the maximum and minimum elastance during a pump cycle [9]. For an HBV tripler, the maximal conversion efficiency can be estimated from the following empirical expression [10]:

$$\eta \approx \frac{100}{1+200\left(\frac{f_p}{f_c}\right)^{1.5}} \ [\%]. \tag{1}$$

How to calculate corresponding optimal embedding impedances, input power, and theoretical limit of the bandwidth was presented by Stake *et al.* [10]. To maximise the efficiency, the above dynamic cut-off frequency should be maximised. Thus, optimum performance is a trade-off between maximum elastance swing and series resistance. The maximal extension of the depleted region is determined by the maximum electric field at breakdown or the effect of current saturation [11, 12]. Hence, the maximum elastance swing is determined by one of the following conditions:

- depletion layer punch-through;
- large electron conduction across the barrier region at high electric fields;
- large electron conduction from impact ionisation at high electric fields;
- the saturated electron velocity in the material determines the maximum length an electron can travel during a quarter of a pump cycle.

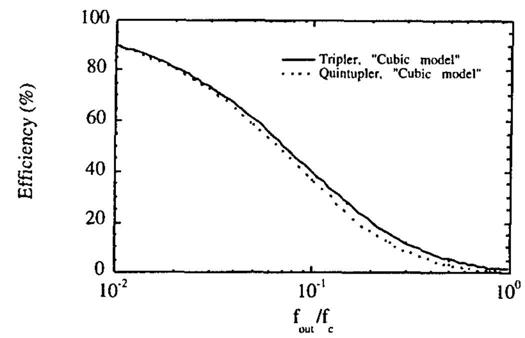

Fig. 2. Maximum tripler and quintupler efficiencies normalised to the same output frequency.

For a given application (frequency and available power) and material system, it is possible to optimise the HBV layer structure in terms of number of barriers, length and doping concentration of depletion layers, see reference [10].

It is interesting to compare quintuplers with triplers as power sources for the same output frequency. A varactor diode is usually dimensioned from the output impedance. Since the output impedances are approximately equal for triplers and quintuplers, triplers and quintuplers with the same diode capacitance can be compared. Referring to Figure 2 it is shown that the maximum efficiencies are almost equal, except for output frequencies near the dynamic cut-off frequency. This indicates that quintuplers have an advantage over triplers, since they use a lower input frequency where more powerful sources are available. The circuit is more complicated for quintuplers since the impedance at the idler frequency has to be optimised.

As discussed previously, the conduction current is a strong limiting factor for the conversion efficiency. The small signal conductance is, as the capacitance, voltage dependent. If the ratio $G_{max}/(C_{min}\omega_p) < 0.1$, the conductance current will not deteriorate the efficiency more than a few tenths of a dB.

Accurate quasi-static models that describe the voltage across the HBV capacitance and the conduction current have been proposed by Dillner *et al.* [13]. For detailed HBV analysis, codes combining time-dependent numerical device analysis with frequency-domain harmonic-balance analysis can be used [14, 15].

IV. HBV FREQUENCY MULTIPLIERS

The first HBV tripler experiment was performed in a crossed-waveguide mount. The single-barrier GaAs/-AlGaAs HBV was contacted with a whisker wire, Rydberg *et al.* [2]. A maximum output power of 1 mW was generated at 225 GHz and the peak flange-to-flange efficiency was 3.1 %.

Fig. 3. Planar 2x2-barrier HBV (NU2003J) design.

The first planar GaAs/AlGaAs HBV diode was tested in a crossed-waveguide frequency tripler, Jones *et al.* [16]. A maximum output power of 2 mW was generated at 252 GHz and the peak efficiency was 2.5 % for a four-barrier device. Cooled measurements on this type of HBVs showed an improvement in efficiency of a factor of three [6]. To reduce the effect of self-heating, a planar four-barrier GaAs/AlGaAs HBV diode with an improved diode geometry (Fig. 3) was fabricated. 4 mW output power and 4.8 % efficiency was obtained at an output frequency of 246 GHz, Stake *et al.* [17].

A planar four-barrier InGaAs/InAlAs HBV diode was tested in a crossed-waveguide frequency tripler, Mélique *et al.* [18]. A maximum output power of 9 mW was generated at 250 GHz and the peak efficiency was 12 %. This is the best HBV multiplier performance obtained so far.

In a new design the InP substrate is etched away and replaced with pure copper, Dillner *et al.* [19]. This offers not only a lower series resistance but also an improved thermal heat sink, which improves the power handling capacity. In a recent tripler experiment using a crossed waveguide mount, Dillner *et al.* [5] (see Fig. 4), and this new diode, a maximum output power of 7.1 mW was generated at 221 GHz with a flange-to-flange efficiency of 7.9 %.

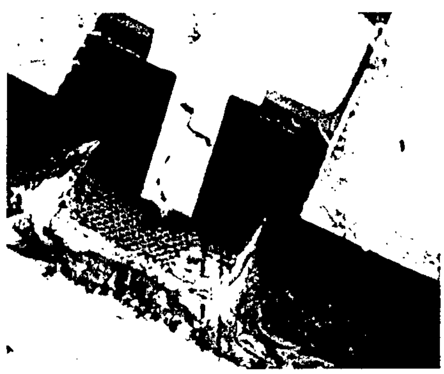

Fig. 4. HBVs on a copper substrate mounted in the output waveguide. The three-barrier HBV is contacted with a planar whisker.

In addition to the crossed waveguide multiplier, two other HBV multiplier topologies, Hollung *et al.* [20, 21], have been developed. One is a broadband distributed HBV frequency tripler consisting of a finline transmission line periodically loaded with 15 HBV diodes, see Fig. 5. This frequency tripler uses planar diodes with two barriers and exhibits 10 mW peak radiated power at 130 GHz with more than 10% 3-dB bandwidth and 7% conversion efficiency.

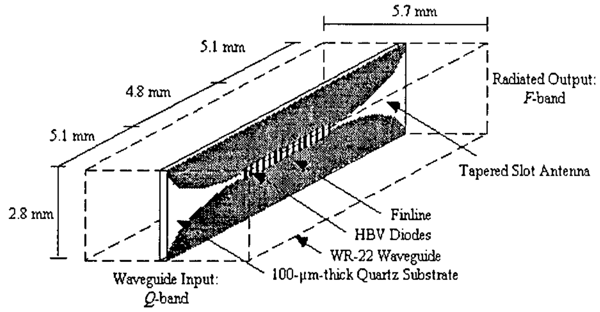

Fig. 5. Non-linear transmission line HBV tripler consisting of two tapered slot antennas and a finline loaded with 15 HBVs on a 100 µm-thick quartz substrate.

The second design is a quasi-optical HBV diode frequency tripler consisting of two slot antennas loaded with four planar HBV diodes and located at the focal plane of a dielectric lens, Fig. 6. The quasi-optical tripler demonstrates a radiated power of 11.5 mW and a conversion efficiency of about 8 %.

Single barrier InGaAs/InAlAs HBV diodes have also been tested in a crossed-waveguide frequency quintupler, Räisänen *et al.* [22]. 0.78 % efficiency was reported at an output frequency of 172 GHz.

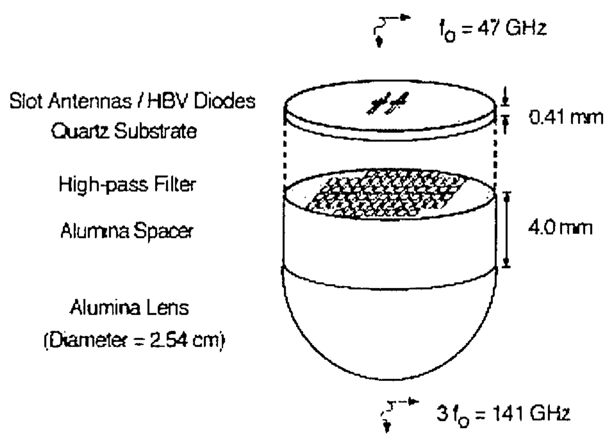

Fig. 6. Quasi-optical HBV tripler. The circuit consists of two slot antennas loaded with four HBV diodes and located at the focal plane of a dielectric lens.

V. Conclusion

The HBV is today comparable to Schottky varactors in terms of conversion efficiency, I-V and C-V predicts superior power handling capability, and the HBV is more suitable for high order frequency multipliers. The performance of planar GaAs/AlGaAs HBV multipliers is severely reduced due to self-heating. This problem can be solved by modifying the epitaxial structure to increase the barrier height and by improving the diode heat sink. High efficiency and wide bandwidth HBV triplers have been demonstrated. We predict that HBV quintuplers will be very competitive as high frequency power sources.

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